Science
Education

Risk-Based Decision Making in a Scientific Issue: A Study of Teachers Discussing a Dilemma Through a Microworld

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ABSTRACT: Risk has now become a feature of science curricula in many industrialized countries. While risk is conceptualized within a number of different theoretical frameworks, the predominant model used in examination specifications is a utility model in which risk calculations are deemed to be objective through technical expert assessment and where the perceptions of individual actors can be corrected by appropriate rationalization of action and thought. However, research studies and other theories on risk suggest that a utility-based approach fails to take into account social, experiential, and cultural factors, which frame what is considered to be risky. Our research study with science and mathematics teachers deploys a microworld, "Deborah's dilemma," which presents a decision-making process involving probabilistic estimates in which teachers construct their own personal models of risk. Teachers were recorded in dialogue while working through the microworld. Inductive coding of the dialogue and interactions with the microworld show that teachers' decisions on risk have a rational underpinning, but that use of data and information only becomes coherent and comprehensible within the explicated values of decision makers. We suggest that designing programs on learning about risk in science must incorporate the opportunity to make values explicit and coordination of different dimensions of risk. © 2012 Wiley Periodicals, Inc. *Sci Ed* **96:**212–233, 2012

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INTRODUCTION

Over the course of the past 20 years, the topic of risk has appeared prominently in science curricula and school educational programs in England (Qualifications and Curriculum Development Agency, 2011), the United States, particularly, the Science Education for Public Understanding Program (2011) with learning units on probability and risk assessment, Australia (Australian Curriculum, Assessment and Reporting Authority, 2011), and other industrialized countries. Moves toward public risk literacy in education (Bader, 1993; Petts, Wheeley, Homan, & Niemeyer, 2003; Riechard, 1993) were echoed by the Nuffield 2000 report on school science education (Millar & Osborne, 1998) in its recommendations for ideas-about-science: "By considering some current issues involving the application of science, pupils should . . . understand the ideas of probability and risk; be aware of the range of factors which can influence people's willingness to accept specific risks . . . " (p. 2022).

Triggers for the inclusion of risk in the U.K. science curricula and examination specifications, and for the development of resource materials (Association for Science Education, 2008; Spiegelhalter, 2010), can be seen to stem from public responses to issues of national concern related to science and technology such as the links between bovine spongiform encephalopathy (BSE) and Creutzfeldt–Jakob disease (CJD), Brent spar and salmonella poisoning in the 1990s, as well as more global effects such as climate change, nuclear accidents from Chernobyl and Three Mile Island, and most starkly the radioactive fallout from the 2011 tsunami in Japan. Despite the many benefits that developments from science and technology have had for society—at least for most people in wealthy industrialized countries—such as increased life expectancy, potable water, and international travel—late modern society has also witnessed deepened public anxiety and fragile trust in science governance (Giddens, 1990). Addressing these concerns, the House of Lords Science and Technology Committee commented in their Science and Society report that "When science and society cross swords, it is often over the question of risk" (House of Lords, 2000).

The advent of technoscientific anxiety underpinned by reflexive awareness of risk has come to be known as the "risk society" (Beck, 1992) although a number of empirical studies suggest that popular anxieties over possibly hazardous events might be overestimated. While worry about risk does not appear to underlie people's intuitive and day-to-day rationalizations (Lupton, 1999), these concerns intensify when specific events such as food safety are brought to the public's attention (European Commission Special Eurobarometer, 2006).

At least one critical voice has questioned whether risk as a component of decision making is intrinsically concerned with knowledge claims in science and therefore comes outside of its epistemological domain (Donnelly, 2006), but the case for, and challenges of, teaching risk in science have been discussed by Eijkelhof (1990, 1996), Lijnse, Eijkelhof, Klaassen, and Scholte (1990), Keren and Eijkelhof (1991), Dillon and Gill (2001), Kolstø (2001, 2006), Ryder (2002), and Christensen (2009). Following a constructivist approach, Eijkelhof's extensive multimethod study (1990) focused on students' prior beliefs, information availability from textbooks and the press, and identified interconnected problems with misconceptions over content and risk assessments. Like Eijkelhof (1990), Dillon and Gill (2001) discussed an understanding of probabilities and teaching risk through different contexts in the science curriculum. Kolstø (2006) probed high school students' decision making about the construction of a high voltage power line through the analysis of argumentation patterns. Laying the power line overground would be cheaper but raises the likelihood of childhood leukemia. Students discussed the relative size of the risks and the use of the precautionary principle but their justifications of the risks involved were drawn from acquiescence to expert assessment of the risks rather than their own reflection on that assessment. In an earlier study of the same socioscientific dilemma, Kolstø (2001) found that students question the sources of risk assessments, often on grounds of trust in relation to the researcher's interest positions, but that the students' analyses tended to be weakly grounded in scientific knowledge claims or understanding of the problems in making risk assessments.

Identifying teaching approaches to address the epistemic aims of citizenship science education, Ryder (2002) advocates a focus on risk in addressing "learning aims related to uncertainty in science" (p. 649) such as the difficulties in making technical assessments of risk, problematized in Kolstø's studies (2001). Christensen (2009) notes understanding and dealing with uncertainty of two kinds as core to making risk-based decisions: uncertainty in terms of the operationalization of science in the real world and the uncertainty of contested science in the making. In addition, decision making in relation to risk has to take into account the social and cultural contexts in which scientific knowledge can be brought to judgment. Introducing ideas of uncertainty as well as social and cultural considerations presents pedagogical demands well outside the comfort zone of science teachers (Bryce & Gray, 2004; Levinson & Turner, 2001).

Within the curriculum in the United Kingdom, the topic of risk can be taught within a diverse range of scientific contexts such as nanotechnology, genetic engineering, and care for the environment, and is now an integral part of preparation for practical work in terms of making risk assessments (Borrows, 2003, 2008; R. Scott, 1998; Tawney, 1992; Taylor, 1992). But what can be inferred from nearly all contexts of its etymology is that risk has two predominant meanings: "damage" as in "What are the health risks from radioactive materials?" or chance/probability/likelihood as in "What factors increase the risk of heart disease?" and is universally associated with negative experiences such as heart disease and risks of melanoma from prolonged exposure to the sun (Cancer Research UK, 2011). That risk can be used with a range of meanings and associations is not surprising: The history of the world has evolved through sociopolitical contexts such as insurance, war, and sport. It is a slippery, contentious, and politically loaded concept.

MODELS OF RISK

If risk does constitute an important part of the curriculum, what might be suitable assessment criteria for judging students' knowledge and understanding of risk, particularly, when the wording of curriculum documents and examination specifications indicates that there are different uses of the term in different contexts? If there is such a thing as "actual" or "objective" risk, or a range of situations when objective risk can be depicted, then teaching needs to focus on expert and rational approaches to defining and solving risk problems, which might take into account popular perceptions of certain unlikely events (Slovic, 1987; Slovic, Fischhoff, & Lichtenstein, 1980). For example, the Salters–Nuffield Advanced Biology textbook (Hall, Reiss, Rowell, & Scott, 2005) defines risk as "the probability of occurrence of some unwanted event or outcome" (p. 20) and that "[P]eople frequently get it wrong, underestimating or overestimating risk" (p. 21). Examination specifications on "How Science Works" *Assessing impacts of science and technology: risk and risk assessment* make distinctions between "perceived risk" and "actual risk" (AQA, 2010). Such explanations of risk are depicted in Figure 1, which distinguishes between the elements of actual risk and perceived risk, where appropriate cognitive adjustments can be made to faulty lay perceptions. On the right side of Figure 2, "actual risk" is defined as the product of the probability of an event occurring and its impact. Factored into this definition of risk are uncertainties intrinsic to science practice such as estimating the maximum allowed toxicity of a substance in which estimated accuracy is refined through

Figure 1. Schematic representation of utility approach.

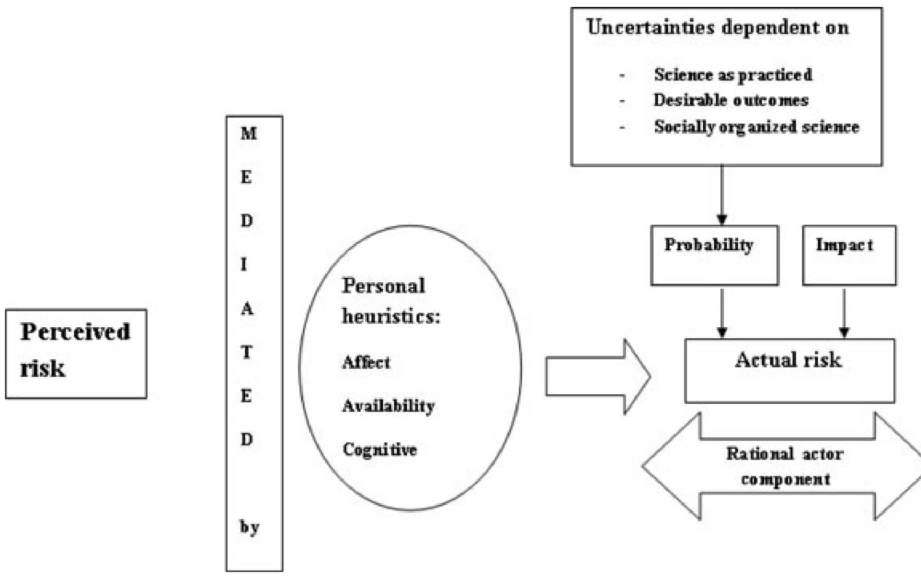

Figure 2. Utility model of risk.

trials. Increased predictability and control of accuracy would then reduce the probability of exceeding toxic limits. Within the realms of expected error, "actual risk" can therefore be quantified. However, the left side of the diagram uses a psychological account to explain why lay people "frequently get it wrong."

Personal heuristics account for discrepancies between an individual's judgment of a risk event (Brandstätter, Gigerenzer, & Hertwig, 2006) and the objective risk calculated by experts (Crossland et al., 1992). Affect (Finucane, Alhakami, Slovic, & Johnson, 2000) includes emotional responses to highly unlikely but fearsome events such as bombs on the metro compared with more common events such as road accidents involving mortalities, availability (Folkes, 1988; Tversky & Kahneman, 1973) in which people draw on information through readily available and familiar sources such as the media, and cognitive heuristics where estimations of the likelihood of an event are integrated into people's experiences and belief systems (Greening, Dollinger, & Pitz, 1996). Attempts to instruct lay people in better estimations of actual risk are encapsulated in the design of the riskometer (American Council on Science and Health, 2002), which orders events in terms of their levels of risk on a logarithmic scale rather like a Richter scale (Ezard, 1999) as well as other similar scales (Buatois et al., 2010).

The curriculum specifications, as represented in Figures 1 and 2, have their roots in the Enlightenment and Benthamite utilitarianism in which the risk taker is conceptualized as a rational actor, motivated by self-interest, who evaluates alternative courses of action and possible outcomes in decision making to maximize happiness (Jaeger, Renn, Rosa, & Webler, 2001). This worldview has been instrumental as the epistemological basis for organizing institutions characteristic of modern industrialized nations, for example, the welfare state, in measuring social norms, and the potential distribution of goods and benefits, and assumes technical expertise in calculating actual risks (Lupton, 1999; National Centre for Social Research, 2003; The Royal Society, 1983). Utility in maximizing happiness becomes a tool through which measurements such as monetary units or some other kinds of goods can be assigned. In this view, risk is real and objective and lends itself to accurate measurement.

But decision making is usually complex. It is relatively, and possibly deceptively, easy to decide on a course of action, where both the possible outcomes and the probabilities for each of these potential outcomes are known. This is the kind of situation involved in gambling on roulette tables or betting on horses. However, in many technoscientific situations such as SARS and global warming and nanotechnology, where scientists frequently disagree about the models on which any prediction of risk can be calculated (Millar, 1997), neither the probabilities nor the outcomes are known—"the injured of Chernobyl are . . . not even born yet" (Beck, 1996, p. 31)—arising in a situation of "ignorance," for example, in the emergent GRAIN (genomics, robotics, artificial intelligence, nanotechnology) technologies, where uncertainties are high and decision stakes are urgent (Ravetz, 2005). Standard risk assessments fail to fully characterize the uncertainties, unknowns, and issues of ignorance associated with the impacts of new technologies (Levidow, 2002).

A crucial problem with rational action and utility models is the assumption that individual interests outstrip all other forms of decision making. Assessing risk in the vast majority of social situations involves more than individual considerations of maximizing utility; it engages the problematic and complex dynamics of conflict or arriving at consensus with other actors refracted through a range of cultural contexts (Douglas, 1992). An example of how risk situations are constructed by different histories, narratives, and experiences was seen in a recent study of preservice teachers' discussions on what constitutes risk when a Nigerian-born science teacher who had had malaria a number of times skeptically responded to a mathematics teacher who was concerned about taking his family to west Africa because of the risk of contracting malaria:

> I was planning a holiday to Africa. Just before we were due to go we heard the malaria risk was much higher because there had been a lot of rainfall and my family decided to stay behind and I went on my own in the end. I suppose that's recognizing some sort of threshold of risk that I might have actually passed. . . I had no figures to work on, no percentage risks for example, you just felt not a good feeling about this. (Mathematics teacher)
>
> To you that's quite a risky thing to do. For someone like me who grew up in Africa and had malaria like about three times, saying the level of malaria has increased, well, I've had it three times so it doesn't seem that much of a big deal. (Science teacher)
>
> (Levinson & Rodd, 2009)

What was seen as a major risk by one person was not perceived as a significant risk by another.

Individuals and communities who draw on "local" knowledges and experiences (Tytler, Duggan, & Gott, 2001) are not necessarily misguided because their judgment differs from that of experts (Irwin, Dale, & Smith, 1996; Layton, Jenkins, Macgill, & Davey, 1993; A. Scott, 2001). Stilgoe (2007) problematizes the management of risk in the case of mobile phone base station health and safety regulations as in the perception by experts of an ignorant and unchanging public. Evolving models of interactions between experts and publics point toward a more reflexive expert perception of public concerns and a realization of the importance of public engagement. Over the past two decades, it is precisely the role of expert advice in, for example, the management of the BSE crisis that was deemed to lead to the "crisis of trust" identified in the House of Lords report (2000).

There are therefore alternative theories to the utility model because of the problems in meeting the complex social and institutional frameworks enveloped in contemporary technoscientific decision making, and anxieties induced by a growing awareness of the fragile political structures governing contemporary technologies (Beck, 1992; Giddens, 2002; Stirling, 1998, 2008). How people respond to challenging events might be influenced both by their own risk thermostats (Adams, 1995), situated, local, and sociocultural experiences (Douglas & Wildavsky, 1982), which govern risk responses and their reflexivities (Giddens, 1990). Or risk can be conceived as situated within a web of late modern discourses underpinned by institutional power relationships (Hall, 2001) in which sectors of citizenry are designated "at risk": pregnant mothers who are at risk of miscarriages unless they follow certain medical procedures; young children at risk through behavior on the internet; incarcerated women at risk of contracting HIV (Paasche-Orlow, Clarke, Hebert, Ray, & Stein, 2005).

Given the range of theories and models of risk, there is no culturally agreed body of theory for teaching and learning, or pedagogical models, on which to build strategies, models, and resources. The utility model incorporated in the curriculum (Figures 1 and 2) needs to be tested and problematized. Since teachers will need support in adopting appropriate strategies and curriculum structures, we start with an investigation into how science and mathematics teachers construct risk when approaching a decision-making scenario.

The path we take therefore is to consider the place of personal models in decision making, for two reasons: (1) we take the view that learning involves the modification of preexisting personal models in interaction with others, rather than learning being a process of replacing learners "wrong" thinking with models of "right" thinking; and (2) it is critical to respect personal models because personal values (as expressions of personal preferences and ethical positions) and social and affective values are inextricable from making decisions.

We chose to work at this stage with a small group of teachers rather than piloting an emergent model in the classroom. The evaluation of the Twenty-First Century science course (Scott et al., 2007) found that "students made progress in understanding in most contexts (though not on the topic of risk)" (p. 8) and therefore teachers needed an opportunity to clarify their own thinking, attitudes toward and understanding of risk in scientific issues free from the contingencies of the classroom. We wanted teachers to engage critically with the core ideas of risk rather than finding appropriate ways of delivering lessons about risk, although teaching effectively about risk presupposes critical engagement. There are also ethical problems in using untested models in the classroom without sufficient teacher reflection. Consider, for example, a teacher discussing the risks of smoking with a group of pupils without being able to internalize and explain to peers the multidimensional nature of the issue in social, ethical, as well as scientific and mathematical terms. Finally, working within a small group offered the opportunity to iteratively respond to and then redesign a model of a specific risk dilemma.

Our research approach draws on technology-enhanced tools because they offer both an opportunity to significantly challenge the nature of personal models and thinking about risk and the potential for researchers to probe more deeply into how people think (Noss & Hoyles, 1996). We chose to work with science and mathematics teachers because

1. risk is not only becoming prevalent in science curricula, but in mathematics curricula too;
2. there are often rigid divisions between subjects in schools (Levinson & Turner,

2001), and this offered the possibility of probing interdisciplinary thinking;
3. insights into how teachers understand risk in a scientific/medical context will enable construction of support materials in teaching and learning trials; and
4. interacting with an information-rich interactive software environment offers a window into probing teacher thinking (Pratt & Yogui, 2010).

Our research question, therefore, is: What are the prevalent factors that influence decision making when paired groups of mathematics and science teachers construct models of risk through a structured microworld based on a utility approach?

METHODOLOGY

Four pairs of science and mathematics teachers, each pair from the same school, were chosen to take part in the project. Three pairs of teachers took part in working with the microworld because one pair of teachers was unable to attend that day; however, our overall research program into teachers' thinking about risk involved all four pairs of teachers. The four science teachers were well known to the lead author through the teacher education partnership between London schools and the higher education institution; they teach at diverse large multiethnic schools in London (one pair were from a fee-paying independent school and the others were from state-funded schools in socially deprived areas); they all had more than 8 years of successful teaching experience, were mentors of preservice teachers, and were willing to collaborate with mathematics colleagues who they contacted in their school over the topic of risk. Because each member of a pair of teachers knew each other well, the discussion was likely to be informal and as frank as possible. While these teachers were keen to engage with the research project, the challenges that arose in interactions with the microworld could be deemed to be representative for science and mathematics teachers more broadly and raised questions for a wider testing of the model. The pairs of teachers were (not their real names): Neil (science) and Tim (mathematics); Linda (science) and Alan (mathematics); and Peter (science) and Ella (mathematics).

After extensive discussions with the teachers about diverse risk situations, we developed a scenario, *Deborah's dilemma*, in which the teachers considered the dilemma faced by a fictitious person (Deborah) about whether to have an operation that could cure a spinal condition that was causing her considerable pain. Teachers were encouraged to put themselves in Deborah's situation. Having the operation would be likely to result in a complete cure but would entail certain hazards, which would need to be discussed by the teachers from various sources of information. Choosing not to have the operation would result in Deborah/the teachers managing her/their lifestyle(s) through daily routines of work, domestic and leisure activity, to alleviate the ongoing pain resulting from the medical condition.

Information about Deborah's condition was set out within the multimedia software[1] in a deliberately personal way to offer different perspectives with varying levels of authority. Data that had been presented ambiguously through consultations, and Web sites were not changed to reflect, as far as possible, the range of data sources that participants would come across naturalistically. The home page presents a brief overview of the condition, and why Deborah has to decide whether to have the operation or continue with the pain. Succeeding pages elaborate on the dilemma. One page headed "The problem" gives a textual account from Deborah of the back pain being a congenital condition, the restrictions on her lifestyle,

[1] The microworld for *Deborah's Dilemma* can be found at www.riskatioe.org.

and the visits she has paid to doctors. There is also an accompanying video of about 2 and $^1/_2$ minutes, where Deborah (not the speaker's real name) explains the nature of the problem in more detail, both in terms of the medical aspects and the effects on her home and work. Following pages explain, through text and video, the sports that Deborah enjoys and those that intensify and ease the pain, the effect of work on her back pain, and her efforts to moderate her working conditions, a page-containing reports from three consultations and Deborah's own personal research.

But we also took care to offer the teachers an opportunity to coordinate probabilities and outcomes as in a standard utility model. Two software tools accompany the information about the condition. The first (*Operation Outcomes*) was a probability simulator in which the teachers modeled the possible consequences of having the operation. The likelihoods for these various complications (i.e., side effects of the surgery, ranging from minor to serious, and even death) were quoted in the information provided in differing forms and from conflicting sources. The teachers were required to draw on the sources and decide which possible complications to incorporate into their model with what they considered to be appropriate probabilities of the operation's success. Hence, the teachers created their own model as an interpretation of the complex information provided.

Figure 3 shows a model in which the probability of success is 70%, and three complications with associated probabilities have been entered. The model has been run 1,000 times. The simulator assumes that an operation that generates a complication is a failure, although failures are recognized that have no complications. On the patchwork representation, we can see the proportion of failed operations and the color-coded breakdown of complications that have arisen from these.

The second tool, the *Painometer* (Figure 4), is a less conventional attempt to give a quantified experience of Deborah's pain, and how different activities may cause it to increase and decrease, relative to a "tolerable" level, where the response to pain is a potentially interesting context for probing personal models of risk. The teachers were required to decide what activities Deborah should or should not do and to infer from the

Figure 3. Probability simulator: operation outcomes.

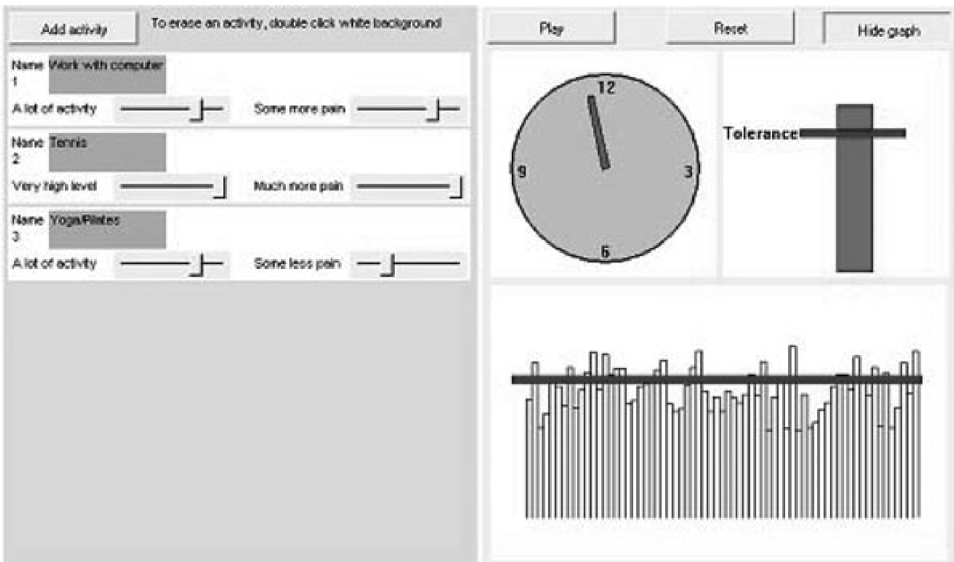

Figure 4. The painometer used to model Deborah's lifestyle.

information the effect on Deborah's pain level due to those activities.

The teachers were able to control Deborah's level of pain tolerance, the amount of work, and domestic, leisure, and sport activity that Deborah does and the pain intensity of each, assuming that some types of work and sport would worsen the pain and others would relieve it. It was also possible to introduce new activities such as shopping and yoga into the model of lifestyle with the aim of looking to see whether a balance could be achieved between pain-inducing and pain-relieving activities, so that the teacher as a vicarious Deborah might achieve a tolerable amount of pain from day to day. The outcomes could be analyzed through the graph and the oscillating gray bar, which show the variation in the level of pain hour by hour in relation to the assumed level of tolerance.

The pairs of teachers worked through *Deborah's dilemma* to consider the options and what decision they might take were they in her shoes. A researcher sat with each group but only intervened to demonstrate relevant aspects of the software, to address any technical points, and to ask questions for clarification. Having arrived at a decision, each pair of teachers wrote a report explaining their reasoning. Video screen capture software recorded the process of decision making through the teachers' dialogs and manipulation of the simulators. The session lasted approximately 2 hours.

Data for the analysis consist of an audio transcript for each pair of teachers, a video record of their interactions with the software, their written account of the reasoning behind their final decision, and notes from each researcher including observations from a "floating" researcher who was able to compare the inference making of each pair.

The transcripts were openly coded in relation to interactions with the software. Themes such as "source of data" were derived from sections of the text of the paired dialogs and recorded when common themes from more than one pair of dialogs had been agreed between researchers (Flick, 2006). These were then cross-checked by a third researcher, disagreements identified and resolved. Groups of statements were then selected and operationalized as empirical indicators of themes and subthemes (Wengraf, 2001).

RESULTS

Source and Interpretation of the Data

All three groups discussed how the relevant probabilities came to be constructed. There were five main themes relating to the source and interpretation of the supplied data:

- questions about the source of the data;
- interpreting the data;
- representing the data;
- comparing risk data; and
- role of trust and authority in mediating the data.

Questions About the Source of the Data. In attempting to make sense of the information available, questions were raised about the provenance of the data. This particularly concerned Tim, intimating differential attributes of authority such as access to information, the relationship between doctor and/or consultant and patient, and how this mediates trust in authority (O'Neill, 2002):

> . . . I'd be quite interested about where they're [the medical professionals] getting their information from. Because I'm wondering maybe how often a doctor updates their data, like was this a study from 2000, 2005? Was it from America, was it from this country, was it from that country? And I'd expect that most of them wouldn't even know.

A few moments later, Tim and Neil expand on why it was important to know in which country the operations were carried out. Although the dialog is jocular, it carries the implication that they are putting more weight on a study from the United States because it is a bigger country than the United Kingdom and the population from which the probabilistic data are drawn is much larger:

> T: That will cloud your judgment slightly, there's a survey done in the U.S. against the U.K. Some people get slightly concerned, but then they'll say 'that's done on a bigger population so it's more reliable' (laughs).
> N: 'I don't care it's America' (laughs).
> T: It's four times the size of this country.

How the figures for the probability were sourced were also problematic for the two other groups who recognized that Web sites might be unreliable (Allen, Burke, Welch, & Rieseberg, 1999) as sources of data:

> P: Now her own research. Reliability, source.
> E: Yes, that is questionable—one list from any old website you don't know, could be one person.

For Linda, the problem with lack of information about the provenance of data could also lead to fear:

> Personal research—well you know going on the internet to look up this kind of information, it freaks you out, you think you have got all sorts . . . (a point echoed by Neil), . . . there's lots of things to be scared about, but that's a risk if you go onto the internet isn't it?

Hence, all parties had a questioning approach where meaning and validity of data was weighted according to the reliability of the source that in itself came with imponderables. The teachers did recognize that the way data were sourced and constructed made it uncertain (Christensen, 2009).

Interpreting the Data. The lack of precision in the data was a problem for all the participants, not knowing whether a 1 in 500 chance meant that this was a maximum or minimum probability and the range covered. For example, in the following dialogue between Linda and Alan, they discuss what probability figure to enter in the probability simulator:

A: Less than one in 500. So one in. . . well shall we go one in 500?
L: Why would they say less than one in 500?
A: It's not very helpful is it?
L: No.
A: One in 512, I don't know.
L: Maybe we should be conservative about it.
A: Again, let's be pessimistic; one in 500.

Similarly lack of clarity in the data also perplexed Peter and Ella:

P: One study, and does not say how many people, and just says "reduced" pain.
E: We could assume the pain had gone completely. But we don't know how many people.

Information provided poses a problem for Linda and Alan when they could interpret the data in different ways, each leading to a different kind of outcome:

A: So 95 to 98% successful. So that's. . . is that 95 to 98% of the time the pain is relieved? Or 95 to 98% of the time there's no complications?
L: That's a good question.
A: So do we know whether. . . there's 95 to 98% here, the success rate it terms of providing relief. . . so that means in about two to five percent, it doesn't actually have an effect at all.
L: But is that long term or short term. . . I mean what's the pain like?

Representing the Data. The teachers preferred to think in terms of actual numbers of people rather than probabilities. Although Neil (below) is using humor when talking about representing information, his point is that probabilistic data have less of an impact on users of information than an account of actual numbers of people (see italicized comment in the following extract):

N: The trachea and the nerve roots are possibly serious.
T: Yeah they could leave her worse than what she was in the first place.
N: In our simulation that was four out of 51 wasn't it?
T: What four out of 1000 operations?
N: Four out of 1000.
T: Out of the failures it was four out of 51. But you've got 51 failures which means 47 operations just didn't work, it just didn't do what it was supposed to do. And out of those four there was possibly serious complications, so that's you know, less than half of a seventh.
N: We've got to decide if we write that. *If we're recommending the surgery then we'll write that, and if we're not recommending the surgery then we'll say four people* (laughs).

How data presentation can influence decision making and is articulated by Tim:

> . . . I mean if you're going to say "60 people died from this procedure," is that enough to tempt someone to say "alright I'll give that a go"? Ok that would look bad because 60 people is more impacting on you than one in 1000, one in 10,000. Those big figures will convince you, but I think "60 people died from this last year" convinces you in a different way, even though the figures, you know that's where the one in 50,000 comes from. The way you present your data is very important to an individual.

The tension between interpreting probabilities and focusing on the person was summarized in Peter's dialog with Ella:

P: It [the probability simulator] was very good as a tool for getting the idea of what the perceived risk is, from the surgery point of view, which was very clinical, these are numbers, studies have shown, research has shown, there is not much to say about it, but then when you looked at her real life, how the condition affects her, the impact of that is massive.
E: Yeah you forget about all the numbers . . .

This point is echoed by Tim despite his commitment to have the operation. "And that's where raw figures go wrong, because raw figures are what they are—stone cold, no emotion, you know there's the facts."

And Linda, for example, intuitively transforms percentages into real people, which is congruent with her emphasis throughout her interaction with *Deborah's dilemma* on focusing on the individual, "5%, that's five people you know." With whole numbers people's fates can be envisaged more easily.

On another occasion, Alan and Linda are discussing the probability of contracting a superbug in hospital and mistranslate a 0.00025% probability as 25 in 100,000, or 1 in 4,000. This is far too high for the current proportion of superbug infections in U.K. hospitals. In paired dialog, it was easy for teachers to miscalculate small percentage values into figures and proportions more commonly used in everyday discourse. Overall, this illustrates a common problem, where people find large numbers and low probabilities difficult to comprehend. It suggests the need to take care in designing materials about risk, possibly highlighting the need to support students and consumers in negotiating and interpreting the ways in which probabilities are represented.

Comparing Risk Data. One of the problems participants found was assigning any personal meaning to probabilities, akin to the kinds of information the riskometer provides, although the riskometer deals with generalized probabilities rather than localized need and impacts. Alan expresses the problem to Linda:

> Do you think the operation is too dangerous? 3 in 1000, I mean we probably take other chances of danger like that all the time without realising. I don't know what they would be, it would be interesting to find out. What do I do that's as dangerous as this? If she does kayaking is that more dangerous? . . . What are the risks of these sports that she does?

Tim and Neil also reflected on the meaning of any probabilistic term, but they suggested that judging how to act on the probability of a particular event would be influenced by how you were positioned in relation to the event:

> . . . to a doctor or a scientist one in 10,000 would be a very low risk [for the back operation], but I think one in 10,000 is quite high.

Often they had to think of other events and activities with which they were more familiar and interpret the data into their own schemata.

Role of Trust and Authority in Mediating the Data. A significant factor influencing decision making was trust in an authoritative body or person giving advice. Weighing trust in those who mediated the evidence or who were going to carry out the operation was crucial to Tim and Neil. Experience was important, but even trying to judge the value of experience was problematic and uncertain:

> Personal things like that carry far more weight; if they've got something on their mind. If the surgeon says they've carried this out 200 times, you say ok, but if someone says they've done it 10 times. I mean they might have done it 10 times and always been successful but they might have done it 200 times and lost 15 patients . . . some operations some doctors would never attempt, they just say it's too risky whereas others say I'll take a chance, you've got a 50% chance of life. Somebody's got to take that risk; it depends on the complexity of the surgery and whether you're going to be dead in a year or something. (Tim)

For Linda, the determining factor that was consistent with her resistance to the operation was the opinion of a specialist:

> OK . . . if . . . the spine guy said "no" then I'm going to say "no." He's said not only these [risks] but these as well, and this is what we can do to help you. This guy knows more about it than the other people, and he's seen more of these people. So I would say no to the operation, I think. (Linda)

Compared with Kolstø's studies (2001, 2006), the teachers problematize the data they are offered in construing justifiable evidence for their decision making. But they also recognize the role of trust and authority in giving meaning to the data.

Outcomes and Impacts

According to utility theory, risk is both the probability of an event occurring but also the magnitude of the outcome and the evaluation of that outcome is a "political, aesthetic and moral matter." (Douglas, 1992, p. 31). The possible impacts of whether Deborah should or should not have the operation were discussed extensively by the three pairs of teachers, although Tim and Neil had decided early on that the operation was the right decision:

> Yeah, I think it's acceptable. . . OK, I can accept if it doesn't go right it might go wrong, OK I won't get any better but I don't want to walk out of here being paralysed or with spine damage or anything. *And I think 4 out of 1000 is an acceptable risk. That's a one in 250 chance*. (Our italics).

Similarly, Peter and Ella also opt to have the operation after calculations on the probability simulator and the painometer:

> On trialling 10,000 operations, there was a 1 in 200 chance of ending up with a complication, i.e., she ends worse than she started. We included up to 4 complications; nerve damage, trachea/oesophagus damage, anaesthetic, and superbug. However, looking at the impact on her life and her pain threshold we reached the decision that she should have the operation much more quickly.

In contrast, Linda and Alan opt for pain relief through management of lifestyle, although they suggest that the operation is not a "prohibitively dangerous option" if the condition worsens.

Although both Neil and Tim are well aware that the operation might go wrong, the overriding consideration for them is the acceptability of the low probability of permanent damage. This is a somewhat surprising outcome because the dialog between them indicates both a sophisticated understanding of the uncertainty of the data used for estimating probabilities (Christensen, 2009; Ryder, 2002) and a sensitivity to the problems of paralysis as Tim's comments on the detached perspective of "raw figures" (see above) suggests.

How personal preferences affect decision making in light of possible outcomes emerges in several dialogs between Peter and Ella, where Peter veers on the side of caution and is inclined to weigh up preventive measures against the operation whereas Ella consistently opts for pain avoidance and aesthetic considerations:

> P: If I was the doctor I would still say, if she warrants it, because there are exercises and stuff—there are things like the special neck brace.
> E: Who wants to walk around with that? No.
> P: I might go for the exercises.
> E: I definitely wouldn't.
> P: The surgery might be very painful, the recovery, I bet you'd have to wear a brace, and you couldn't eat food. I think you'd be in hospital a long time.
> E: But would you, how do you know?

Linda and Alan initially have a similar view to Peter that means of managing the pain would be a better outcome than the low probability of an adverse outcome from the operation. But later, Alan changes his mind and opts for the operation because, mirroring Ella's reason, the constant pain would make life too difficult. "There's still pain, no matter what she's doing, always pain" (Alan).

In terms of practical outcomes, Ella and Alan also feel that the operation would at least eliminate all inconveniences in the context of Deborah's everyday life, even if there is a chance of permanent paralysis (in which case Ella prefers death as an outcome):

> Driving is significant, otherwise she's got to bus or cycle, and she can't carry bags. I would definitely have the operation. (Ella)

Acknowledging and foregrounding personal preferences in decision making through realistic scenarios of risk events is therefore an important consideration because once effects on Deborah's personal and active life are weighed up, thoughts about possible impacts trump any estimates of probabilities.

How attitudes toward and considerations of lifestyles played themselves out in decision making were very pertinent in relation to the dialog between Linda and Alan and weighing up impacts on lifestyle. Linda, who both consistently foregrounds the terrible suffering endured in the unlikely event of the operation going wrong, and keeps in mind that these are real people rather than probabilities, focuses on the ameliorating effect of changes in lifestyle, as can be seen in exchanges with Alan:

> A: There's still pain, no matter what she's doing, always pain.
> L: But she's still alive.
>
> A: And work is difficult, so supporting herself is difficult. She has to take time off work.
> L: She's lived with it for a while, and she's looking.
>
> A: You need someone to do your shopping for you . . .
> L: Well, she can use a trolley . . .

Hence the major factors underpinning the decision were preference for a lifestyle either free from pain or one that could be managed without having the operation. While there was some discussion of probabilities, these only interacted with the decision on outcomes in a marginal way or provided insufficient background for a decision to be made.

Empathy and Experience

All three pairs drew on their own experiences, those of friends, vicarious or anecdotal evidence to buttress their opinions. Sometimes in the case of Tim, the lesson from a personal experience went counter to his decision and was in fact used to show that individuals could react differently to the same experience depending on their emotional relationship to it:

> I mean this has got a personal aspect for me; it's no major problem but I've had it for a while. And also on the case of the anaesthetic side; there's a relative who's died from that about five or six years ago . . . minor operation; like no risk, virtually zero risk. I must admit it's never affected me, in terms of thinking about operations; I've only had one operation in my life and I was so young, your parents make the decision for you. But it certainly didn't affect the way I've thought, you know, operations do go wrong, and that's the way. But it did have a big impact on the family, and on my parents generation; it had a big impact on them. But for me, there was an impact at the time but it's just like ok, that's the way it was. I wouldn't say it's changed my opinion of surgery. (Tim)

Alternatively, Linda and Alan drew on experiences of others they knew or had read about which would influence having the operation or lifestyle:

> A: For someone who does a lot of physical activity; you know, it supposedly keeps you healthy, and it actually does bring with it other risks.
> L: I'd've thought swimming or something would have helped. There was this man on the telly last night and he was 70 or something playing football, and he was so healthy.

A: Yeah. Have you not got friends though who have done lots of running and their knees are done already? You know like 25 and they can't run on roads anymore.

For Linda, in particular, consideration of the impact of the operation going wrong on Deborah and her family was a highly influential factor in her decision making:

> Shall we try not having the op? That's enough, looking at how horribly wrong it could go for her . . . we haven't even talked about her family and stuff . . . if it went wrong and people depended on you. You do think of other people when making these choices. (Linda)

A willingness to accept a level of probability resulting in irreversible harm or even death operates alongside an ambivalence toward those authorities who produce and publish the risk data. There is supporting evidence, which demonstrates public skepticism of technically assessed risks (George et al., 2004), but in certain circumstances to accept expert advice in a relationship of trust (Stilgoe, 2007). The difficulty here is that the teachers articulate sound reasons that they simply do not know enough for them as individuals to make a sensible assessment of the probability estimates that have been given, that they have good reason to doubt that doctors have full command of the data, yet a probability of 1 in 200 becomes acceptable. A possible explanation is that what can be done about the level of pain, the social context of the sufferer, willingness to accept responsibility for the decision, and how risk is apprehended through lived experiences are determinants of the kinds of odds people are likely to accept.

The same factors in other contexts are likely to be prevalent for young people at school which would mediate decision making, although their analyses of how probabilistic estimates are constructed are unlikely to be as sophisticated as that of the teachers, as evidenced by Kolstø's research (2001, 2006). In constructing personal estimates of risk within a strongly defined narrative, what appears to characterize teachers' decisions is not a sophisticated application of probabilistic judgments—although there is clear evidence of evidence-based reasoning about the possible outcomes of the operation—but values explication, including trust, empathy, and social awareness—"if it went wrong and people depended on you . . . You do think of other people when making these choices" (Linda)—and an awareness of ambivalence and complexity.

DISCUSSION

Responses of the teacher pairs to the data suggest that the utility model (Figures 1 and 2) does not sufficiently account for discrepancies in estimations of objective and perceived risk; on the contrary, we would argue that distinctions between perceived and actual risk do not reflect how reasonable participants make risk estimations. The decision cannot be inferred from the articulated reasoning derived from the medical data, but the incorporation of values, storied experiences, and hesitations act as qualifiers and provisos in influencing decisions. In fact, the journey from risk estimation to decision has had much less research than the study of risk itself (Davis & Hersh, 1986) although from a utility perspective, Papadouris and Constantinou (2010) have documented difficulties in sixth-grade school students in systematically optimizing solutions from simple data sets in open-ended tasks. Skepticism of data, attitudes toward authority, empathy, trust, personal responses to pain levels, and ethical considerations about lifestyle located in personal experiences appear to be highly salient factors, which impinge on decision making for the teachers and frame the level of risk. Even when individuals are dealing with relatively simple and nonlife threatening situations, such as gambling stakes, there are likely to be experiential considerations such as the advisability of spending money on a bet, and how personal circumstances might dictate how you responded to any putative loss, which add layers of complexity to the situatedness and construction of risk. While the evidence from teachers' dialog suggests that five of the six teachers (Linda being an exception) made initial decisions based on stochastic reasoning, the teachers were aware of how these problematic estimates might be framed; interpreting probabilities was one of a variety of interacting factors in influencing their final decision.

In the case of positioning in relation to authority, it becomes clear that teachers adopt contradictory positions. Although experts themselves might have problems and biases in the way they present and source data, most operations are successful and the teachers know how to filter out exceptional events.

Difficulties lie in the ways in which the teachers weigh probabilistic information against lifestyle changes. There were relatively few instances where the teachers simultaneously balanced changes in lifestyle against the likelihood of the operation resulting in serious harm. This might have been a problem in the way the data were presented, but it was more likely that personal preferences were driving decisions irrespective of the emerging evidence. There is only one clear change in viewpoint and that is when Linda explains to Alan that she would place most trust in the surgeon who advised against the operation. Of the six participants, Linda was most equivocal about the operation, was generally discomfited by the probability data, and from the beginning looked for a way of improving lifestyle to avoid having the operation.

The microworld allows participants to make both their reasoning and beliefs explicit and suggests that teaching from a utility perspective, as most curricula depict risk, does not accurately reflect real-life decision-making processes. Examination and curricular specifications do not encourage students to develop personal models with all the complexity and situated richness presupposed in personal decision making. While there are good justifications for teaching probability, neither subject knowledge of science nor expertise in manipulating probabilities appears to be sufficient conditions for personal decision making about this health issue. There were many opportunities in the microworld for the teachers (the three science teachers taking part were all biologists) to make use of relevant scientific knowledge in helping to evaluate risk, but none chose to do so, reflecting other accounts, where scientific knowledge and information are either marginal or irrelevant to lay decision making (Dawson, 2000; Layton, et al., 1993; Ryder, 2001).

We suggest that meaning derived from risk data such as probabilities presupposes explication of personal values and preferences. Any quantitative estimation of probabilities and impact can only have meaning for the learner through an enquiry-based approach (Pratt & Yogui, 2010) in which there has been an opportunity to make explicit values, experiences, and representations of those experiences and probabilities that foreground the decision-making process, and where probabilities can be judged in light of, and interact with, expressed values. A model for estimating risk in teaching and learning situations is therefore proposed in Figure 5.

COORDINATING THE DIMENSIONS OF RISK: PROBABILITIES AND OUTCOMES

Although teachers had the opportunity on the *Deborah's dilemma* microworld to reflect on the various outcomes or "futures" of the operation together with possible changes in lifestyle and family impacts, this rarely occurred. Tim and Neil made their decision directly using probabilities as a post hoc rationalization and only discussed changes to lifestyle later. Linda and Alan and Peter and Ella focused first on changes to lifestyle before considering

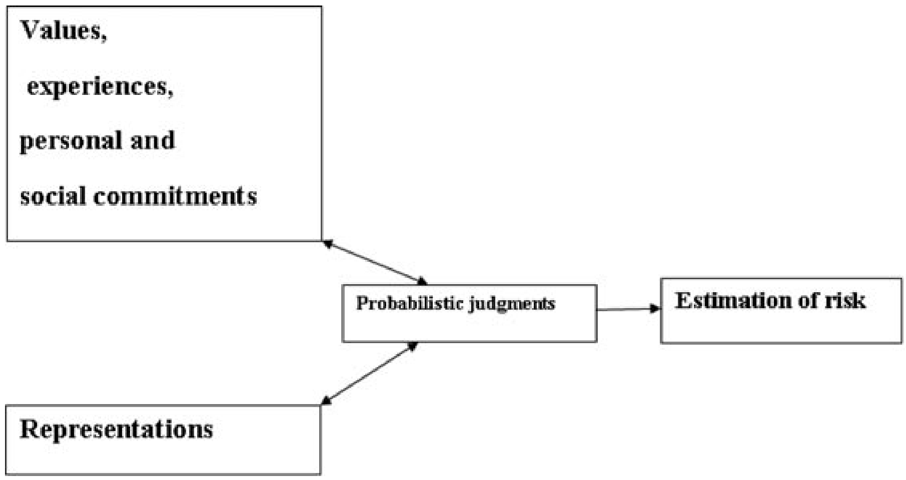

Figure 5. Pedagogic model of risk.

probabilities separately. Possibly because of strong empathy with Deborah's situation, particularly from Linda and Alan, who focus on ways of alleviating the condition and trusting the more authoritative consultants without having the operation, weighing possible outcomes of the operation with outcomes of changes to lifestyle were not evident in the discussion. One interpretation is that the context of the scenario did not encourage this coordination, but it is more likely to simulate how participants approach decision making given the rich data available.

We have therefore incorporated a mapping tool (Figure 6) into *Deborah's dilemma,* which allows participants to coordinate the large amount of complex and often contradictory information on Deborah's condition, operation, and lifestyle. The provision of decision

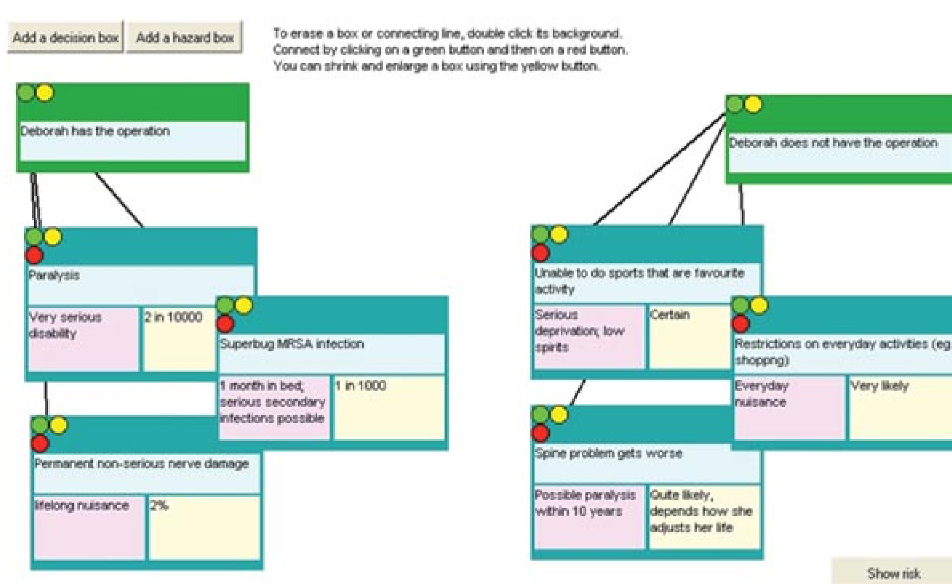

Figure 6. Mapping tool.

boxes enables participants to structure the information in accordance with their priorities and the probabilistic information at their disposal. These boxes can be moved around in accordance with participants' decisions as to which factors are most important and can then provoke discussion promoting the coordination of probability estimation with value considerations. A short pilot research project carried out with 14- to 15-year-old students indicates that this might be an aid to making their own assessments of risk visible to themselves as well as to others. A core implication of our research is that this tool supports discussion of sociocultural meaning within which estimations of probability and impact can be embedded.

IMPLICATIONS

While *Deborah's dilemma* represents one situated study, teachers' interactions with the microworld suggest that pedagogy for risk taking invokes both an opportunity to provide students with events that consist of uncertain outcomes to which probabilities and their representations can be assigned and students' articulation of attributes such as social awareness, personal experience, and trust in relation to the probabilities. Such opportunities can be provided by giving students authentic conditions in which decision making involving weighing different outcomes can be operationalized. However, what counts as "authentic" in a science context is itself contested (Braund & Reiss, 2006; Hume & Coll, 2010; Murphy, Lunn, & Jones, 2006; Prins, Bulte, Van Driel, & Pilot, 2008). The distinction of Murphy et al. (2006) between cultural authenticity in which students engage in science-based discourses through issues of mutual social concern and personal authenticity, which relates to what is relevant in their learning, is a useful one. In a school context, it allows students to engage with risk-based scenarios that either reflect school-based issues and local action such as recycling, use of mobile phone in schools, and personal contexts such as genetic tests or use of sunbeds for tanning (Levinson 2011). Scenarios structured like *Deborah's dilemma* could support students' engagement with risk assessment incorporating values explication and be adapted to diverse contexts and test the validity of the microworld as a means of constructing a personal understanding of risk in a particular context. However, further research is needed to identify the opportunities and barriers for learning and decision making in these kinds of scenarios.

REFERENCES

Adams, J. (1995). Risk. London: Routledge.

Allen, E. S., Burke, J. M., Welch, M. E., & Rieseberg, L. H. (1999). How reliable is science information on the Web? Nature, 402, 722.

American Council on Science and Health. (2002). Riskometer.org: Putting risk in perspective. Accessed November 30, 2011, at http://riskometer.org/.

AQA. (2010). Science in society. Accessed November 30, 2011, at http://store.aqa.org.uk/qual/gce/pdf/AQA-2400-W-SP.PDF.

Association for Science Education. (2008). SATIS revisited: Taking risks. Accessed November 29, 2011, at http://www.satisrevisited.co.uk/takingrisks.asp.

Australian Curriculum, Assessment and Reporting Authority. (2011). The Australian curriculum. Accessed November 30, 2011, at http://www.australiancurriculum.edu.au/Home.

Bader, R. (1993). Overcoming false public beliefs-possible strategies for improving environmental risk literacy. Toxicological and Environmental Chemistry, 40(1–4), 275–288.

Beck, U. (1992). Risk society: Towards a new modernity. London: Sage.

Beck, U. (1996). World risk society as cosmopolitan society? Ecological questions in a framework of manufactured uncertainties. Theory, Culture & Society, 13(4), 1–32.

Borrows, P. (2003). Managing health and safety in primary science. Primary Science Review, 79, 18–20.

Borrows, P. (2008). Health and safety in practical science in schools: A UK perspective 2, using model risk assessments. Science Education International, 19(4), 415–418.

Brandstätter, E., Gigerenzer, G., & Hertwig, R. (2006). The priority heuristic: Making choices without trade-offs. Psychological Review, 113(2), 409–432.

Braund, M., & Reiss, M. (2006). Towards a more authentic science curriculum: The contribution of out-of-school learning. International Journal of Science Education, 28(12), 1373–1388.

Bryce, T., & Gray, D. (2004). Tough acts to follow: The challenges to science teachers presented by biotechnological progress. International Journal of Science Education, 26(6), 717–733.

Buatois, S., Perret-Guillaume, C., Gueguen, R., Miget, P., Vancon, G., Perrin, P., et al. (2010). A simple clinical scale to stratify risk of recurrent falls in community-dwelling adults aged 65 years and older. Physical Therapy, 90(4), 550–560.

Cancer Research UK. (2011). Melanoma risks and causes. Accessed November 30, 2011, at http://www.cancerhelp.org.uk/type/melanoma/about/melanoma-risks-and-causes.

Christensen, C. (2009). Risk and school science education. Studies in Science Education, 45(2), 205–223.

Crossland, B., Bennett, P. A., Ellis, A. F., Farmer, F. R., Gittus, J., Godfrey, P. S., et al. (1992). Estimating engineering risk. In F. Graham-Smith (Ed.), Risk, analysis, perception, management. London: The Royal Society.

Davis, P. J., & Hersh, R. (1986). Descartes' dream: The world according to mathematics. London: Penguin Books.

Dawson, C. (2000). Selling snake oil: Must science educators continue to promise what they can't deliver? Melbourne Studies in Education, 41(2), 121–132.

Dillon, J., & Gill, P. (2001). Risk, environment and health: Aspects of policy and practice. School Science Review, 83(303), 65–73.

Donnelly, J. (2006). The intellectual positioning of science in the curriculum, and its relationship to reform. Journal of Curriculum Studies, 38(6), 623–640.

Douglas, M. (1992). Risk and blame: Essays in cultural theory. London: Routledge.

Douglas, M., & Wildavsky, A. (1982). Risk and culture: An essay on the selection of technical and environmental dangers. Berkeley: University of California Press.

Eijkelhof, H. M. C. (1990). Radiation and risk in physics education. Utrecht, The Netherlands: Uitgeverij CDβ Press.

Eijkelhof, H. M. C. (1996). Radiation risk and science education. Radiation Protection Dosimetry, 68(3–4), 273–278.

European Commission Special Eurobarometer. (2006). Risk issues. Accessed November 30, 2011, at http://ec.europa.eu/public_opinion/archives/ebs/ebs_238_en.pdf.

Ezard, J. (1999). Riskometer measures life's ups and downs. Accessed November 30, 2011, at http://www.guardian.co.uk/uk/1999/jul/16/johnezard.

Finucane, M. L., Alhakami, A., Slovic, P., & Johnson, S. M. (2000). The affect heuristic in judgments of risks and benefits. Journal of Behavioral Decision Making, 13, 1–17.

Flick, U. (2006). An introduction to qualitative research (3rd ed.). London: Sage.

Folkes, V. S. (1988). The availability heuristic and perceived risk. Journal of Consumer Research, 15(1), 13–23.

George, G., Allum, N., Wagner, W., Kronberger, N., Torgersen, H., Hampel, J., et al. (2004). GM foods and the misperception of risk perception. Risk Analysis, 24(1), 185–194.

Giddens, A. (1990). The consequences of modernity. Cambridge, England: Polity Press.

Giddens, A. (2002). Runaway world: How globalization is reshaping our lives. London: Profile Books.

Greening, L., Dollinger, S. J., & Pitz, G. (1996). Adolescents' perceived risk and personal experience with natural disasters: An evaluation of cognitive heuristics. Acta Psychologica, 91(1), 27–38.

Hall, A., Reiss, M. J., Rowell, C., & Scott, A. (2005). Salters–Nuffield advanced biology. Oxford, England: Heinemann.

Hall, S. (2001). Foucault: Power, knowledge and discourse. In M. Wetherell, S. Taylor, & S. J. Yates (Eds.), Discourse theory and practice (pp. 72–81). London: Sage.

House of Lords. (2000). Science & technology—Third report. Retrieved May 25, 2011, from http://www.publications.parliament.uk/pa/ld199900/ldselect/ldsctech/38/3801.htm.

Hume, A., & Coll, R. (2010). Authentic student inquiry: The mismatch between the intended curriculum and the student-experienced curriculum. Research in Science and Technological Education, 28(1), 43–62.

Irwin, A., Dale, A., & Smith, D. (1996). Science and Hell's kitchen: The local understanding of hazard issues. In A. Irwin & B. Wynne (Eds.), Misunderstanding science. Cambridge, England: Cambridge University Press.

Jaeger, C. C., Renn, O., Rosa, E. A., & Webler, T. (2001). Risk, uncertainty, and rational action. London: Earthscan.

Keren, G., & Eijkelhof, H. M. C. (1991). Prior knowledge and risk communication: The case of nuclear radiation and X-rays. In R. E. Kasperson (Ed.), Communicating risks to the public: Technology, risk and society (pp. 145–156). Dordrecht, The Netherlands: Kluwer.

Kolstø, S. D. (2001). "To trust or not to trust, . . ."—Pupils' ways of judging information encountered in a socio-scientific issue. International Journal of Science Education, 23(9), 877–901.

Kolstø, S. (2006). Patterns in students argumentation confronted with a risk-focused socio-scientific issue. International Journal of Science Education, 28(14), 1689–1716.

Layton, D., Jenkins, E., Macgill, S., & Davey, A. (1993). Inarticulate science? Driffield, England: Studies in Education Ltd.

Levidow, L. (2002). Ignorance-based risk assessment? Scientific controversy over GM food safety. Science as Culture, 11(1), 61–67.

Levinson, R. (2011). Teaching controversial issues in science. In R. Toplis (Ed.), How science works: Exploring effective pedagogy and practice (pp. 56–70). Abingdon, England: Routledge.

Levinson, R., & Rodd, M. (2009). Pre-service teachers' conceptions of risk: A pilot study. Revista de Estudos Universitários, 35(2), 85–99.

Levinson, R., & Turner, S. (2001). Valuable lessons. London: The Wellcome Trust.

Lijnse, P. L., Eijkelhof, H. M. C., Klaassen, C. W. J. M., & Scholte, R. L. J. (1990). Pupils' and mass-media ideas about radioactivity. International Journal of Science Education, 12(1), 67–78.

Lupton, D. (1999). Risk. London: Routledge.

Millar, R. (1997). Science education for democracy. In R. Levinson & J. Thomas (Eds.), Science today: Problem or crisis? (pp. 87–101). London: Routledge.

Millar, R., & Osborne, J. (1998). Beyond 2000: Science education for the future. London: King's College.

Murphy, P., Lunn, S., & Jones, H. (2006). The impact of authentic learning on students' engagement with physics. Curriculum Journal, 17, 229–246.

National Centre for Social Research. (2003). Health survey for England 2003. London: Department of Health.

Noss, R., & Hoyles, C. (1996). Windows on mathematical meanings: Learning cultures and computers. London: Kluwer.

O'Neill, O. (2002). Autonomy and trust in bioethics. Cambridge, England: Cambridge University Press.

Paasche-Orlow, M. K., Clarke, J. G., Hebert, M. R., Ray, M. K., & Stein, M. D. (2005). Educational attainment but not literacy is associated with HIV risk behavior among incarcerated women. Journal of Women's Health, 14(9), 852–859.

Papadouris, N., & Constantinou, C. P. (2010). Approaches employed by sixth-graders to compare rival solutions in socio-scientific decision-making tasks. Learning and Instruction, 20, 225–238.

Petts, J., Wheeley, S., Homan, J., & Niemeyer, S. (2003). Risk literacy and the public—MMR, air pollution and mobile phones. London: Department of Health.

Pratt, D., & Yogui, C. (2010). A constructionist approach to a contested area of knowledge. Paper presented at the Constructionism 2010 Conference, Paris, August 2010.

Prins, G., Bulte, A., Van Driel, J., & Pilot, A. (2008). Selection of authentic modelling practices as contexts for chemistry education. International Journal of Science Education, 30, 1867–1890.

Qualifications and Curriculum Development Agency. (2011). National curriculum. Accessed November 30, 2011, at http://curriculum.qcda.gov.uk/index.aspx.

Ravetz, J. (2005). The no-nonsense guide to science. Oxford, England: New Internationalist Verso.

Riechard, D. E. (1993). Risk literacy: Is it the missing link in environmental education? Journal of Environmental Education, 25(1), 8–12.

Ryder, J. (2001). Identifying science understanding for functional scientific literacy. Studies in Science Education, 36, 1–44.

Ryder, J. (2002). School science education for citizenship: Strategies for teaching about the epistemology of science. Journal of Curriculum Studies, 34(6), 637–658.

Science Education for Public Understanding Program. (2011). Decision-making: Probability and risk assessment. Accessed November 30, 2011, at www.sepuplhs.org/middle/modules/decision/index.html.

Scott, A. (2001). Technological risk, scientific advice and public "education": Groping for an adequate language in the case of GM foods. Environmental Education Research, 7(2), 129–139.

Scott, P., Ametller, J., Hall, K., Leach, J., Lewis, J., & Ryder, J. (2007). Knowledge and understanding: Executive summary. Accessed November 30, 2011, at http://www.nuffieldfoundation.org/sites/default/files/c21-evaluation_report.pdf.

Scott, R. (1998). Issues of safety in the school laboratory: Pupils perceptions of risk. School Science Review, 79(289), 71–73.

Slovic, P. (1987). Perception of risk. Science, 236(4799), 280–285.

Slovic, P., Fischhoff, B., & Lichtenstein, S. (1980). Facts and fears: Understanding perceived risk. In R. C. Schwing & W. A. Albers (Eds.), Societal risk assessment: How safe is safe enough. New York: Plenum Press.

Spiegelhalter, D. (2010). Understanding uncertainty. Accessed November 30, 2011, at http://understandinguncertainty.org/node/233.

Stilgoe, J. (2007). The (co-)production of public uncertainty: U.K. scientific advice on mobile phone health risks. Public Understanding of Science, 16(1), 45–61.

Stirling, A. (1998). Risk at a turning point? Journal of Risk Research, 1(2), 97–109.

Stirling, A. (2008). Science, precaution, and the politics of technological risk: Converging implications in evolutionary and social scientific perspectives. Annals of the New York Academy of Sciences, 1128, 95–110.

Tawney, D. (1992). Assessment of risk and school science. School Science Review, 74(267), 7–14.

Taylor, P. (1992). Reaction and over-reaction: Risk assessment in science teaching. School Science Review, 73(264), 15–25.

The Royal Society (1983). Risk assessment: Report of a Royal Society study group. London: Royal Society.

Tversky, A., & Kahneman, D. (1973). Availability: A heuristic for judging frequency and probability. Cognitive Psychology, 5(2), 207–232.

Tytler, R., Duggan, S., & Gott, R. (2001). Dimensions of evidence, the public understanding of science and science education. International Journal of Science Education, 23(8), 815–832.

Wengraf, T. (2001). Qualitative research interviewing: Biographic narrative and semi-structured methods. London: Sage.